RECENT ADVANCES IN OPTICALLY CONTROLLED DISCHARGES

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ABSTRACT

The recent increase in modular pulsed power systems has amplified the potential of optically controlled discharges where stringent synchronization in time is required. This interest has lead to new switching applications and concepts as well as new understanding of the switching process from a fundamental standpoint. The increasing diversity of wavelengths available has necessitated a modification of the generally accepted laser-initiated breakdown mechanism. Advances in high time resolution diagnostics techniques have as well allowed a deeper insight into heretofore conjectured mechanisms.

New understanding in optically controlled discharges and new applications since the last review (1977) will be addressed. These include the impact of short wavelength lasers, applications to surface discharges, their application in opening switches including the potential of optogalvanic effects which are of particular significance in diffuse discharges. One additional area of considerable promise is photoconductive switching using intrinsic solid state materials. That advance should be compared to optical control applications on traditional workhorses such as thyratrons. There is no question but that the potential of optically controlled discharges is only beginning to be realized, primarily as a result of improvements in laser versatility and reliability, efficiency of interaction of the optical control energy (particularly in a resonant mode), demonstrated precise timing and synchronization capability to below a picosecond and improved understanding of the total switching event. Possibilities of optically controlled discharges not yet demonstrated will also be discussed.

INTRODUCTION

In recent years there has been a resurgence in interest in laser triggered switching (LTS). This interest has been generated in part by modular pulse power systems, particle beam fusion devices, weapons effects simulators and high power lasers. These, and several other technologies place stringent requirements on switch synchronization or place a premium on electrical isolation of the triggering device from the energy store. In both instances LTS offers distinct advantages.

In the intervening years since the author's review of LTS[1] several new directions have evolved which have made significant impact not only on the field of LTS but on the broader field of optically controlled discharges. Advancements include the use of fiber optics to alleviate difficult optical alignment and cleanliness procedures, shorter wavelength lasers which have opened exciting possibilities, harnessing of the optogalvanic effect for the control of diffuse discharges, and surface discharge phenomenon.

Early work in laser triggered closing switches dealt with such issues as dielectric type[2,5], optical arrangements for introducing the laser into the spark gap[2,6], range of voltages triggerable[7], multiple breakdown paths to reduced inductance[1], and the ability to trigger spark gaps with low incident laser power[8]. Recent work has sought to further reduce switch jitter with reduced laser power, to reduce the level of optical sophistication necessary to operate and maintain laser triggered switches and to search for exotic effects which will allow very high repetition rate, further laser power reduction, and hopefully solutions to the difficult and pressing problem of opening switches.

REQUIREMENTS

The major interest in LTS continues to be in gas-filled spark gaps. The reasons for this include: ease of handling and maintenance of gas systems, gas dielectrics are rapidly self-healing, generally lower stored energy in the interelectrode volume, versatility with easily variable dielectric constant controlled by gas mixture and pressure, ease of introducing special additives for specific purposes, and relatively simple optics compared to other dielectric media except with the possible exception of vacuum. Because of this interest, this type of switch insulator has been studied more than others and as a result a more complete understanding of the switching mechanism has been developed for gas-filled gaps. In general, short delay times and low switching jitter are requirements for switching. Because delay varies as 1/P the pressure usually needs to be high for a particular fill gas.[1] High pressure is not always desirable, thus, a way to reduce pressure while maintaining low delay and jitter is required. One answer is to use an electronegative gas such as SF_6 which has a large voltage hold off capacity. In triggering schemes utilizing IR and visible wavelength lasers, the radiation is best focussed onto one gap electrode usually after being directed through an aperture in the opposing laser entrant electrode. At practical laser power densities a very tenuous plasma is created in the interelectrode space along which the breakdown propagates. Because SF_6 is very electronegative this tenuous concentration of electrons is extinguished unless the delay is short. This necessitates either operating the gap very near the self breakdown voltage or the use of large laser powers. Both of these are undesirable to most practical switching situations: the former because of the increased risk of pre-fire and the latter for economic and longevity reasons. The solution to those conflicting characteristics had to await the development of reliable shorter wavelength lasers.

Very large, very energetic pulse power systems usually must be constructed in modular form. The advantages in doing this include limits on manufacturing technology, safety, in that energy is stored in smaller packets, reduction of current which any switch must carry, graceful degradation vice catastrophic failure in the event of switch pre-fire. The penalty to be paid, of course, is increasingly stringent requirements in terms of synchronization of multiple switches. A case in point is the Sandia National Labs PBFA light-ion-beam fusion driver[9] which is to employ 36 gas switches, each designed to hold up to 2.8 MV. Simultaneity of better than a few nanoseconds is usually required in order to deliver full power in the necessary risetime and pulse shape. Pure SF_6 is the fill gas of choice. As mentioned previously, the use of SF_6 reduces safety and engineering problems associated with elevated pressure and large gap spacing which would give unacceptably high inductance. A difficulty is the optical alignment of the laser with a multitude of switches and tailoring the delay in each gap to account for laser time of flight

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14. ABSTRACT
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differences or, alternately, finding a way to eliminate the time of flight differences. As will be seen, technology advancements have made solutions to these problems possible.

The most difficult problem in switching is the high-power, rep-rated opening switch. Inductive energy storage is attractive because the stored energy density is some 10^2-10^3 times higher than capacitive storage[10]. Opening switches are needed in order to fully realize the potential of inductive storage systems. They are also useful in pulse waveform shaping. Crowbarring or turning off a discharge on command is not an intractible problem but it certainly has proven to be a formidable challenge. Modification of the impedance of the discharge or the concentration of charged species are two methods which have been looked into for producing a high-power opening switch. Work on some interesting phenomena has provided encouraging results. A solid understanding of the switch mechanism is desired in order to properly choose operating characteristics. Operation of the gas filled switch from a triggering standpoint has been well understood for some time. However, improvements in high-time resolution techniques has allowed a keener understanding of some of the more fundamental processes involved.

INNOVATIONS/IMPROVEMENTS

Prior to the advent of LTS one of the better methods for triggering spark gaps was with UV radiation incident upon the gas dielectric. It was well known that UV radiation preionized the gas which lead to formation of Townsend Avalanches and, depending on conditions, initiated subsequent streamer formation. It was quite natural that with the development of lasers operating in the UV[11] an attempt should be made to use them to trigger gas-filled spark gaps. In an early description of a UV laser triggered spark gap, Rapoport, et. al[12] report significant results. Whereas most IR and visible LTS is done by focussing the laser radiation on one of the electrodes it was postulated that the low UV breakdown threshold of SF_6 could best be used to advantage by focussing the laser in the center of the gap. The laser was introduced into the gap via a hollow electrode similar to the earlier visible/IR triggering arrangement as shown in figure 1.

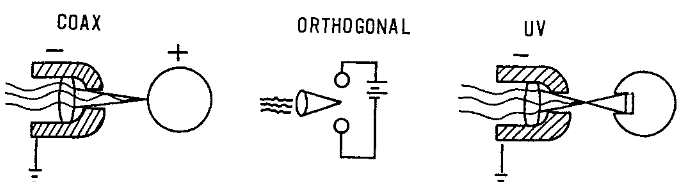

Fig. 1. Long Wavelength vs. UV triggering schemes.

To quote the excellent article by Rapoport, et. al.: "Long Wavelength radiation is absorbed in a gas when free electrons are accelerated by inverse bremsstrahlung and the transfer of significant amounts of energy to the plasmas, therefore, requires the presence of a few free electrons. The production of those free electrons requires either a multiphoton ionization, which is a rare event for long wavelengths, or the presence of impurity particles in the focus. There is, therefore, an infinitesimal but finite statistical time jitter in the closing of the switch since the initiation of the gas breakdown depends upon rare events."

"Absorption of short wavelength radiation proceeds by different processes. Multiphoton ionization in the UV requires only two or three photons and hence has a high probability for intensities above about 10^{10} W/cm^2. At the same time inverse bremsstrahlung absorption, which is proportional to λ^2, becomes much less important. This removes the statistical nature of breakdown in the gas and affords a sharp intensity threshold for formation of a breakdown plasma".

We point out that IR or UV LTS involves electrodes and gas dielectric pressures to different degrees, but one would be foolish not to utilize the advantages of both processes.

Fortunately, SF_6 combines some of the most desirable characteristics of the perfect dielectric for a gas-filled UV triggered switch. Because of its excellent dielectric constant it can be used at relatively low pressures in gaps with small spacing thus affording a low inductance, safe switch. Happily, SF_6 also has a low breakdown threshold for UV radiation. Rapaport et. al. used a 248 nm KrF laser of 7 mJ output in 20 ns to trigger a low-inductance pulser charged to 80 kV dc. Using a 25 cm focal length lens with the 75 µrad divergence of the laser gave an intensity on focus that was adequate to cause SF_6 breakdown. It was found that minimum delay and jitter was obtained when the laser just missed grazing the entry and egress holes in the electrodes. Additional delay and jitter arose when the laser exited the center of the aperture and curiously enough increased when the laser impinged on the electrode! The former increase was probably due to completion of the breakdown channel to the edge of the hole, however there is no explanation advanced for the latter observation. (It could have been due to a geometric limitation of the laser energy). Early work by the present authors[6] showed that the breakdown arc in LTS was quite linear with the exception of branching or a kink near the aperture for the laser due to balance between laser guiding and residual breakdown fields. This disruption could, indeed, increase delay and contribute to jitter although the authors did not investigate this possibility. Very impressive switching performance was observed by Rapoport, et. al. With the gas pressurized to 120% of the spontaneous dc breakdown pressure for 80 kV charging the delay and jitter were 7 ns ± 100 ps. At a pressure of 10 atmospheres, which was 400% of the self breakdown pressure, delay and jitter increased to about 12 ns ± 1 ns.

Because KrF lasers are readily available which have 200 - 400 mJ output, the possiblity to synchronize about 50 switches to within 100 ps seems very real. The group at Sandia National Labs of Woodworth et. al. has made several significant contributions to UV laser triggering of gas switches[9,13,14]. Following the lead of Rapoport et. al.[12], the Sandia group utilized an electrode arrangement in which the KrF, 248 nm radiation exited an aperture in the grounded anode, was focussed near center of the gap and passed into a recess in the charged cathode. The major thrust of their effort was to develop reliable switching of the thirty-six - 2.8 MV switches necessary to deliver the particle beams in the PBFA I light ion fusion device. In this experiment they used a 200 mJ laser with relatively poor beam divergence (5 mrad) to trigger a 500 kV SF_6 insulated gap. The gap was pulse charged and the laser was fired at 80% of the self breakdown voltage (SBV). The delay and jitter were 25 ns ± 2 ns. Because this performance is not adequate to the PBFA I requirements the laser was modified by spatial filtering in an oscillator - amplifier configuration to produce 120 mJ at a divergence of

100 μrad. Using this system a delay and jitter of 2 ns ± 150 ps (1σ) was obtained for voltages in excess of 70% of SBV. Two other experiments were conducted at this time, by the same group. In one study, two gas mixtures were used in a parametric study of switching delay and jitter. A mixture of 10% SF_6/90% N_2 has a dielectric strength 50% that of pure SF_6. Whereas 2650 Torr of SF_6 yielded a 500 kV breakdown voltage and required 120 mJ for a jitter of 150 ps, 3300 Torr of the 10/90 mixture gives a 360 kV breakdown and required only 48 mJ for 160 ps jitter. Finally, a mixture of 10% SF_6, 75% N_2, and 15% Ar gave triggering results significantly worse than those obtained with either of the other gas choices. The remaining experiment will be discussed below in conjunction with the use of additive molecules.

In a later study[9] Woodworth et. al. investigated a full-up model, except for current flow, of the 2.8 MV switch needed for the PBFA I device. A change was made from the previous work in that the charged cathode was not hollowed out thereby allowing the KrF radiation to impinge upon it. Remarkable results were obtained in which delay and jitter of 10 ns ± 500 ps were recorded at 80% of the self breakdown voltage. In fact, subnanosecond jitter was obtained for voltages above 75% of SBV. A parametric study versus laser energy and focal length of the focussing lens was performed. Subnanosecond jitter was obtained at 80% SBV for energies as low as 40 mJ. The range of delay varied little between 80-90% of SBV being only 1.5 ns for 120 mJ and 3.3 ns for 40 mJ. It was also noted, in agreement with Guenther and Bettis[15], that switch jitter remains low as long as the delay is less than the effective laser pulse duration, but increased rapidly for longer delays. Figures 2 and 3 reveal this behavior.

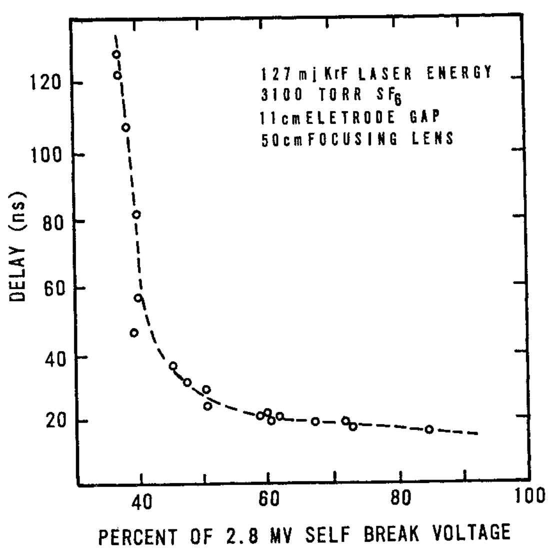

Figure 2. Graph of delay versus voltage for 2.8 MV, KrF laser-triggered switch with 127 mJ of laser energy focused by a 50-cm focal-length lens. Note that the "low-jitter" triggering region extends below 60 percent of the self-break voltage of the switch (After Woodworth, et al)[9]

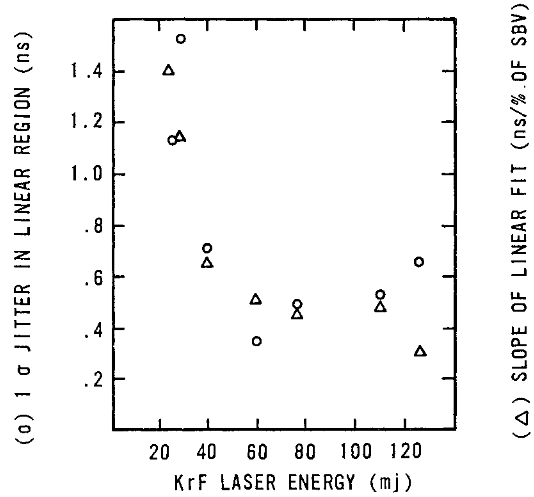

Figure 3. Graph of the 1-σ jitter and the slope of the linear-fit line of delay versus voltage as a function of laser energy. Both jitter and slope rise sharply for laser energies below 40 mJ (After Woodworth et al)[9]

In a third report by Woodworth et. al.[13], a very interesting comparison was made between IR and UV switching. A Nd: YAG at 1064 nm and at the fourth harmonic of 266 nm was used in the investigation. The gap had a 500 kV SBV, insulated with SF_6 and with a 1.77 cm spacing. Figure 4 which is reproduced here, shows the great difference between IR and UV triggering.

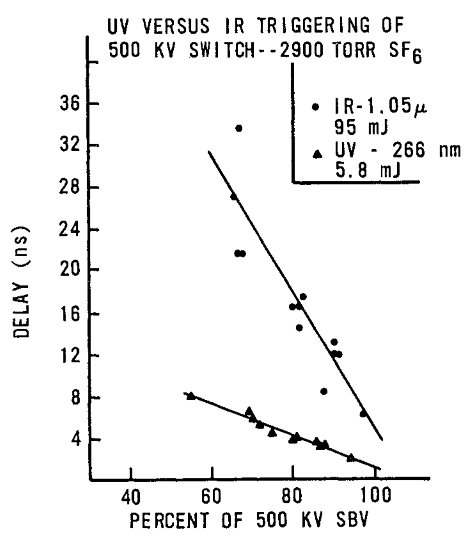

Figure 4. Nd-YAG triggering of 500-kV switch. Comparison of triggering with UV (2-ns) and IR (4-ns) pulses (After Woodworth, et al)[14].

Note how much steeper the slope of delay vs % SBV is for 1.06 μm vice 266 nm even though the energy at 1.06 μm is a factor of some 16 times larger. In both cases the laser was focussed in the center of the gap. They also performed an experiment to show that

jitter was much smaller when the delay was less than the laser pulse width. Both 2 ns and 4 ns, 5.5 mJ (nominal) pulses were used to trigger the switch from 55-90% of SBV. The longer pulse indeed did result in lower jitter.

In a direct comparison with previous IR triggering techniques, they focussed the 266 nm radiation on the cathode but failed to trigger the gap. They also noted that it is immaterial whether the mid plane focussed radiation strikes the cathode or passes through it.

It should be noted that earlier attempts at LTS using UV lasers[16,17,18] suffered from low available energy (~ 250 μJ) and could not produce significant gas breakdown. Thus, the lasers were focussed on an electrode (typically the cathode) which resulted in switching, albeit with unsatisfactory performance.

OPENING SWITCHES

The reader's attention is directed to an excellent article by Schoenbach, Kristiansen, and Schaefer[20], wherein the mysteries of opening switches are explored. To those versed in closing switches in which the switch impedance is driven from near infinite to near zero it may seem that the opposite effect is necessary. Fortunately, clever circuits have been derived which, for example, can divert the current in the switch to a lower impedance load by causing a rapid but non infinite increase in the switch impedance. One way in which the laser could be used is by relying on the optogalvanic effect to increase the impedance of a discharge channel. In the paper by Schoenbach, et. al.[20], optical control of diffuse discharges was discussed as an opening mechanism for rep-rated switches. They state that diffuse discharges can be sustained or terminated by use of positive or negative optogalvanic effects. They further state: "There are two methods for using the optogalvanic effect in opening a diffuse discharge switch. In the first concept, the laser is used to sustain the diffuse plasma, that means to keep its conductivity at a certain level by means of photoionization, allowing a reasonable current flow through the switch. After turn-off of the laser, the conductivity is reduced due to recombination and attachment processes in the plasma, and the switch "opens". To obtain a fast reduction of conductivity (rapid opening), the plasma should be attachment-dominated during the opening phase. This is a requirement which determines the type of gases usable in diffuse discharge opening switches. For a second concept, laser induced loss processes (e.g. attachment) are used to reduce the plasma conductivity. For this concept, the way the discharge is sustained is independent of the control mechanism during the opening phase." The advantages of using the optogalvanic affect is that it is essentially a resonant phenomenon which changes the electrical properties of a discharge with radiation at a wavelength range corresponding to an atomic or molecular transition. Such resonant behavior increases the efficiency of interaction between the laser and the plasma thereby reducing the laser power requirements. The authors consider the gas properties appropriate to utilization of the optogalvanic effect and conclude that two concepts are most promising: (a) discharge sustainment by two-step photoionization from an excited state in NO using an N_2 - NO-attacher gas mixture, and (b) discharge termination through controlled increase of attachment rate by selective vibrational excitation of gases like HCl. The authors are aware of one successful demonstration in which a helium discharge has been turned off by injection of laser radiation.[31]

Certain additives in the dielectric gas can prove very beneficial in LTS. As an example Woodworth, et. al.,[13] investigated resonant, two-step ionization of some organic molecules as a possible means of lowering the UV laser power density required for switching. They list four organic molecules which show great promise of producing two-photon ionization at 248 nm compared to the four photons required to ionize SF_6. Because of the very high electronegativity of SF_6 the mixture chosen was 3500 Torr of N_2 with 28 ppm of Tripropylamine (TPA). The 1-σ jitter for voltages above 80% of SBV was ± 1.0 ns compared to considerably larger delay and jitter for pure N_2. A disadvantage of this technique compared to UV triggered pure SF_6 is that "the slope of the delay versus voltage curve is relatively steep , with delay changing by 10ns between 90% and 80% of SBV. This compares to about a 1.5 ns change for pure SF_6. It has the advantage of being triggerable by a less expensive, commercially available UV laser and indeed by a non-laser UV source as will be seen.

In a study of rail-gap switches, Taylor and Leopold[21] used a fluorocarbon additive to provide multichannel breakdown in a low-inductance gas-insulated rail-gap switch. "The approach most commonly used to initiate multichannel breakdown in a rail-gap switch is to employ a sharp knife-edge electrode either as one of the two main electrodes in a self-breakdown mode of operation or as a third trigger electrode. The rapid application of a high-voltage pulse to the edge electrode produces large temporal and spatial electric field gradients which result in the initiation of multiple channels."[21] In a previous study by Taylor et. al.[22] it was shown that multichannels could be initiated by a few mJ of unfocused eximer laser radiation by using an edge electrode arrangement and a low ionization potential gas additive (fluorobenzene). The problem to solve was how to remove the erosion-prone edge electrode while maintaining multiple channel breakdown. One method, suggested by Harjes, et. al.[23] would be to introduce the laser radiation into the gap with a fiber optics bundle. The authors found, however, that this added complexity was unnecessary if the electrode geometry, gas mixture, polarity, and spatial distribution of the UV radiation were properly chosen. The laser of choice was KrF because its photon energy (5eV at 248 nm) readily yields two-photon ionization in a variety of additive gas molecules. Wavelengths longer than this lose such advantage and current shorter wavelength lasers don't yet produce enough power density for efficient switching. The electrodes were near uniform field profile with a field enhancement factor $f \leq 1.2$ for the anode and $f = 1.0$ for the cathode with a blended in flat on its surface.

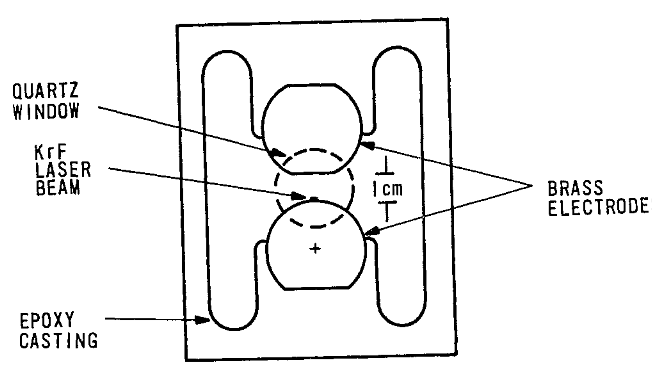

Figure 5. Cross section of the laser-triggered rail-gap switch (After Taylor and Leopold)[21]

It was found, in agreement with previous work[1] in similar gas mixtures, that for E/P greater than 20 Volts/cm-Torr that switch performance improved when the laser radiation was directed at or near the grounded anode. A gas mixture of 50% Ar (enhances multiple channels), 0.75% SF_6 (reduces corona), a few ppm fluorobenzene (two-photon absorption enhances electron production) and the balance N_2 (for dielectric strength) was found to be best. Excellent parametric studies were completed by the authors showing delay and risetime as a function of: laser injection time, KrF laser intensity, laser radiation location, E/P, and reciprocal pressure. Results were in substantive agreement with earlier reported single channel work[1]. Overall results were extremely encouraging yielding ~ 30 channels/meter with a switch jitter of ~ 100 pps using only a few mJ of KrF radiation. In a final study reported by these authors a corona discharge was used to produce a UV line source which reduced previously reported[24] 20 ns jitter in a non-coherent UV produced multichannel rail-gap switch, to ~ 1 ns. The switch consisted of near uniform field electrodes using the same gas mixtures as for the laser triggered experiment. The authors hope to be able to scale-up this switch in voltage with a more powerful corona source.

Utilizing a UV laser to produce multiple channels in a more traditional switching arrangement shows great promise. The major concern in multichannel operation is equal sharing of current by the channels. Once a single channel starts to conduct the voltage across the gap is reduced and even if subsequent channels bridge the gap their share of the current will always be less than that of a fully developed arc. Thus, simultaneity of channel formation is paramount. Charlie Martin[25] has stated that closure jitter between channels must be less than 10% of the single channel risetime. In a study by the present authors[1] it was shown that risetime versus simultaneity between two laser triggered channels supported this statement. Figure 6 shows the data taken on a 360 kV gap.

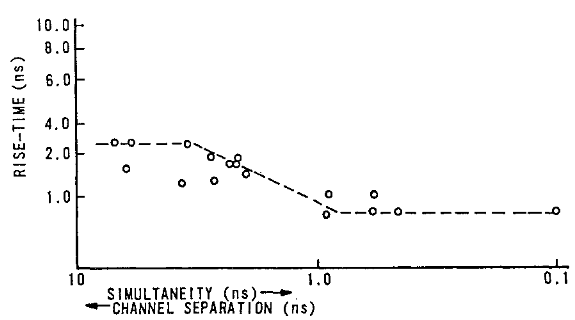

Figure 6. Rise-time versus channel simultancity for two-channel laser-triggered switching in 83% Ar-17% N_2. SBV= 360kV, V= 80-85% SBV, d=3 cm. S=13.34 cm, P= 400 psi, laser power per channel 63 MW (After Guenther and Bettis)[1]

The 3.4 ns risetime was halved when the two channels were simultaneous to better than 0.9 ns. The simultaneity was varied by adjusting the laser power ratio in the two channels. More recently[26] the authors participated in a project to replace an overvolted water switch on the NRL VEBA with a multichannel, command fired, laser triggered gas switch. In the previous experiment the laser beam was split spatially or geometrically whereas in the latter it was split by partial reflectors. The experimental results agreed well with those predicted by computer simulation, showing about a 50% decrease in the 10%-90% risetime with two channels versus one.

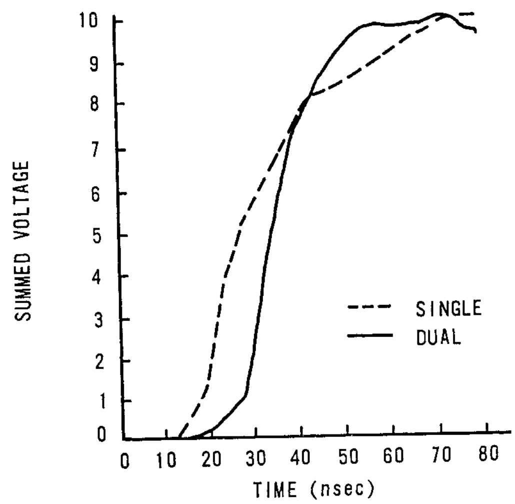

Figure 7. Digitized Traces of Single versus Dual Channel Voltage Rise. (After Bettis et al)[26]

With the use of very precise UV laser triggering, multichannel switching should be very predictable. The major drawback on the VEBA switch was the very difficult and precise optical alignment that was necessary. First time alignment required the presence of an optical physicist with many years experience in laser and LTS. A way around this problem may be available by the use of fiber optics.

In the introduction to their paper, Harjes et. al.[23] state: "The principal advantages of (LTS) are electrical isolation of the trigger from the high voltages, controllable switching delay, and subnanosecond jitter. On the other hand, the optical system which relays the laser beam to the gap requires access to the gap, precise alignment, protection from environmental degradation, and can introduce additional safety requirements. The above inconveniences have been overcome through the use of an optical fiber to conduct the triggering light pulse from the laser to the spark gap. Several advantages are immediately apparent. Optical fibers may be routed through conduit over circuitous paths, eliminating many alignment considerations. Precise time delays may be added by introducing measured lengths of fiber. Also, the use of multiple fibers, illuminated by the same laser to trigger several gaps synchronously, or to initiate several parallel arc channels simultaneously, appears to be a reasonable extension of the technique." They go on to describe using a 15 ns ruby laser pulse to produce subnanosecond jitter LTS of a pulse-charged Blumlein generator gap with voltages up to 250 kV. A parametric study was completed of delay and jitter vs relative percentage of A and N_2 gas and as a function of voltage across the gap. In a later study by Harjes et. al.[27] dual channel triggering of a Blumlein generator gap was accomplished by splitting a ruby laser beam and transporting the two portions via optical fibers to the gap.

The enhanced space charge associated with the cathode as target gave 90% probability for dual channel initiation under the proper conditions. Reliable dual channel initiation for an undervolted gap was not attainable due to the limited laser power which the optical fibers could pass without damage. One must

probably combine the fiber optics approach, short wavelength lasers, and dielectric additives to enhance ionization to produce a truly reliable multichannel capability.

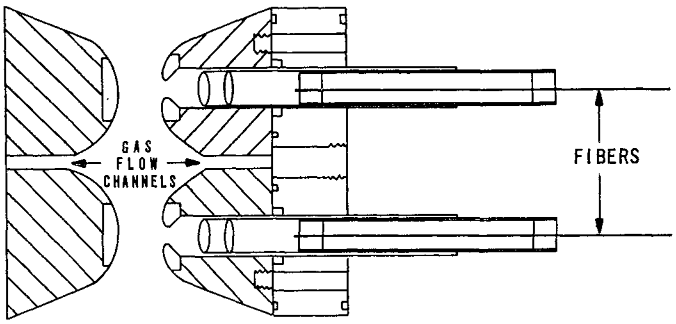

Figure 8. Output optics and electrodes (After Harjes et al)[27]

In a very interesting study, Itoh et. al.[28] report LTS of a N_2/SF_6 filled gap with about 5 ns jitter (1-σ jitter < 1.0 ns) . The optical fiber used is a step-index type fused quartz with 0.5 dB/m loss at power densities less than 3.9 MW/cm^2 and 2 dB/M at 100 MW/cm^2. Using a 2 M fiber the authors observed an exit radiation angle of approximately $\pi/6$ radians. No attempt was made to focus the radiation as it was allowed to fall onto the cathode out of the anode. In lieu of this the performance was amazing. Had the radiation been focused mid-plane and perhaps an additive organic molecule employed, some really outstanding results would undeniably have been achieved. One awaits follow on efforts with anticipation. This technology promises subnanoscond jitter triggering of multiple spark gaps as well as multichannel switching.

Little practical use has been found for laser triggered, solid insulated spark gaps. The fact that solids are generally not self-healing makes their use as dielectrics difficult. However, a class of laser triggered, solid state devices has been receiving a lot of attention since the light activated semiconductor switch (LASS)[29]. Williamson et. al.[30] reported, in 1982, on a laser triggered Cr: GaAs sparkgap. They discuss two principal mechanisms for laser triggering of semiconductor switches. In one case a relatively large laser energy is used to directly photonize all the charge carriers. Photon energies must be on the order of the bandgap of the semiconductor. An advantage is that risetimes equal to the laser pulse duration result. A second type switches high voltages "by inducing only a few charge carriers which then multiply in a carrier avalanche, due to the applied voltage."[30] Their switch employed the latter mechanism. Prior to entry of the YAG laser pulse a small thermal carrier current flows. The laser produces additional charge carriers which drops the resistance and allows up to seven orders of magnitude increase in the current. It was found that 4.0 kV could be switched into 50 Ω with < 1 ns risetime with energies as low as 35 nJ. Control of both delay and jitter were achieved by controlling the laser intensity. We reproduce here their comparison of semiconductor spark gaps with other spark gap designs.

	Semiconductor Sparkgaps	Other Sparkgaps
Hold off	~ 80 kV/cm	up to 500 kV/cm
Build-up time when switched close to self-breakdown	0.5 to 1.5 ns depending on field, trigger energy, and material	$\gtrsim$ 1.5 ns depending on field, trigger energy and pressure
Rise time	conservatively ~ 700 ps in a noncoaxial geometry all shots	$\gtrsim$ 150 ps in well matched geometries
Build-up time jitter	$\gtrsim \pm 150$ ps for 90% of all shots	$\gtrsim$ 150 ps average deviation
Trigger energy	$\gtrsim 5 \times 10^{-8}$ J	$\gtrsim \times 10^{-5}$J

After Williamson et al[30]

A very clever arrangement by Mathur et. al.[31] resulted in nanosecond square pulses at multikilovolt levels with 40 ps risetimes. The device consisted of a commercially available laser triggered spark gap (LTSG) and two cubes of $CdS_{0.5}Se_{0.5}$ as shown in figure 9.

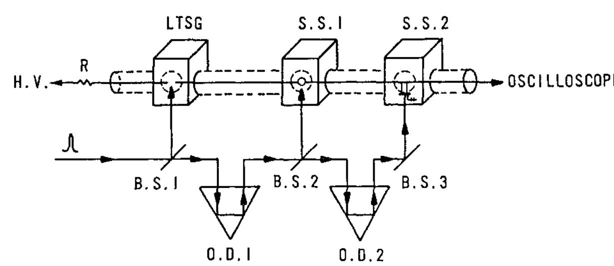

Figure 9. Schematic for multikilovolt switching. R-charging resistor, LTSG-laser-triggered spark gap, SS-semiconductor switch in a pressurized chamber of impedance 50 Ω, BS-beam splitter, OD-optical delay.

The purpose of the LTSG is to isolate the solid state switches from the d.c. bias. This allows a much higher bias voltage in the pulsed mode for the solid state devices. The operation is as follows: The laser pulse is split by B.S.1 into the LTSG which results in conduction of a high voltage pulse to bias S.S.1. The laser pulse is suitably delayed to allow full bias (accounting for delay and jitter of the LTSG) to reach SS1. The laser pulse then switches on SS1 by conventional charge carrier production allowing the voltage pulse to pass through. A second solid state switch (SS2) is connected between the central conductor and ground. When this switch is closed the reflected pulse turns off SS1. The second optical delay determines the width of the switched out electrical pulse. This scheme has two advantages over commercially available LTSGs: (1) reduction of switch jitter to a few picosenconds and (2) improved risetime of the switched out pulse which is of order 40 ps.

SUMMARY

The authors hope to have shown the most important developments in LTS since their review article of seven years ago. The exciting possibilities opened by such advances as high-power short-wavelength lasers, additive gas molecules, optogalvanic effects, high-power fiber optics, and solid state switching have only now begun to be realized. We form the modest hope that laser-triggered switching will be around for some time to come.

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